TABLE 2-8. Adjustments to Measured Level for a 20% Gated UWB Signal

UWB Signal Permutation:	5 MHz PRF, No Mod, 20% Gate
Measured Break-Lock Level:	-94.5 dBm/20 MHz
Individual Power Adjustments	
Conversion to dBW	-30 dB
Correction for GPS signal level (i.e., from -130 dBm used in measurements to -134.5 dBm used in threshold development)	-4.5 dB
Power in a single spectral line (-10log 5, where 5 represents the number of lines contained in the 20 MHz measurement bandwidth)	-7 dB
Adjustment for gate-on time relative to total time (-10 log 5)	-7 dB
Adjustment to compute power in a single spectral line that is modulated by a $sinc^2$ function by the gating period	-7 dB
Total Power Adjustment	-55.5 dB
Adjusted Break-Lock Level (-94.5 dBm - 55.5 dB)	-150.0 dBW
Interference Threshold Developed in RTCA and ITU-R	-150.5 dBW

2.2.3 Analyses of Aggregate UWB Measurements

The results of Case I show that, if the individual interference signals cause an effect that is noise-like, the aggregate signal will be noise-like with the power of the effective aggregate interfering signal determined by summing the average power of the individual UWB signals. For Case I, the measured break-lock level was -87.5 dBm/20 MHz and the reacquisition threshold was -94.5 dBm/20 MHz. These values can also be adjusted for comparison to existing noise-like interference protection levels using the procedures of Section 2.2.2. The adjusted reacquisition threshold is -142 dBW/MHz; that compares to the existing limit of -140.5 dBW/MHz.

The results of the Case II measurements show that an aggregate signal can "fill in" the off periods of the low duty cycle interference at the IF filter output. This results in the UWB aggregate signal of Case II showing an interference effect that is noise-like. The single signal effect for the UWB parameters used was pulse-like. The power level of the effective aggregate interfering signal is determined by summing the average power of the individual UWB signals. For Case II, the measured break-lock level was -79.5 dBm/20 MHz and the reacquisition threshold was -86 dBm/20 MHz. These values can also be adjusted for comparison to existing noise-like interference protection levels. The adjusted, measured reacquisition threshold (including a 7dB factor to compute the average power for a signal with 20% gating) is -140.5 dBW/MHz; that compares to the existing limit for noise-like interference of -140.5 dBW/MHz.

TABLE 2-9. Adjustments to Measured Level for a UWB Signal Employing OOK Modulation and 20% Gating

UWB Signal Permutation	5 MHz PRF, OOK, 20% Gate
Measured Break-Lock Level	-90.5 dBm/20 MHz
Individual Power Adjustments	
Conversion to dBW	-30 dB
Correction for GPS signal level (i.e., from -130 dBm used in measurements to -134.5 dBm used in threshold development)	-4.5 dB
Division of power between discrete spectral lines and continuous spectrum for OOK	-3 dB
Power in a single spectral line (-10log 5, where 5 represents the number of lines contained in the 20 MHz measurement bandwidth)	-7 dB
Adjustment for gate-on time relative to total time (-10 log 5)	-7 dB
Adjustment to compute power in a single spectral line that is modulated by a $sinc^2$ function by the gating period	-7 dB
Total Power Adjustment	-58.5 dB
Adjusted Break-Lock Level (-90.5 dBm - 58.5 dB)	-149.0 dBW
Interference Threshold Developed in RTCA and ITU-R	-150.5 dBW

TABLE 2-10. Adjustments to Measured Level for a Noise-Like Signal

Signal Permutation	Baseline Noise
Measured Reacquisition	-91.5 dBm/20 MHz
Individual Power Adjustment	
Conversion to dBW	-30 dB
Correction for GPS signal level (i.e., from -130 dBm used in measurements to -134.5 dBm used in threshold development)	-4.5 dB
Conversion from 20 MHz measurement bandwidth to 1 MHz reference bandwidth	-13 dB
Total Power Adjustment	-47.5 dB
Adjusted Reacquisition Level (-91.5 dBm - 47.5 dB)	-139.0 dBW/MHz
Interference Threshold Developed in RTCA and ITU-R	-140.5 dBW/MHz

The results of the Case III aggregate measurements showed that line spectra, if produced by one or more sources, can be the dominant cause of interference to GPS. The interference effect in Case III is CW-like; this is further indicated by the CW lines appearing in the measurements of the aggregate spectrum for Case III.[47] Because the interference is attributable to a single interfering CW signal that is coincident with a dominant GPS C/A-code line the aggregate signals do not add to determine the effective interfering signal power. Of course, in the case of an aggregate interfering signal that is a composite of several sources having line spectra, the increased number of potential interfering lines would be expected to increase the probability of coincidence with a dominant C/A-code line. It is also expected that, if there were a very large number (central limit theorem) of signals with line spectra, one would see an aggregate signal that would produce a noise-like effect. For this Case, the measured break-lock level was -109 dBm/20 MHz and the reacquisition threshold was -109 dBm/20 MHz These values can be adjusted for comparison to existing CW-like interference protection levels. The adjustments consider that one of the lines from a 10 MHz PRF UWB signal will be the cause of the interference and that three of the aggregated signals were gated on 20% of the time. The adjusted reacquisition threshold is -154.1 dBW; that compares to the existing limit of -150.5 dBW.

The results of the Case IV measurements again showed that line spectra are the dominant cause of interference. The interference effect in Case IV is CW-like; this is further indicated by the CW lines appearing in the measurements of the aggregate spectrum for Case IV[13]. Because the interference is attributable to a single interfering CW signal that is coincident with a dominant C/A-code line, the aggregate signals do not add to determine the effective interfering signal power. Of course, in the case of an aggregate interfering signal that is a composite of several signals having line spectra, the increased number of potential interfering lines would be expected to increase the probability of coincidence with a dominant C/A-code line. It is also expected that, if there were a very large number (central limit theorem) of signals with line spectra, one would see an aggregate signal that would produce a noise-like effect. For this case, the measured break-lock level was -88 dBm/20 MHz and the reacquisition threshold was -90 dBm/20 MHz. These values can be adjusted for comparison to existing CW-like interference protection levels. The adjustment considers that one of the lines from the 3 MHz PRF signals will be dominant. The adjusted reacquisition threshold is -148 dBW; that compares to the existing limit of -150.5 dBW.

The results of the Case V measurements also show that an aggregate signal condition can "fill in" the off-periods of the low duty cycle pulses at the output of the GPS receiver IF filter. This is further illustrated by the step-by-step introduction of individual UWB signals to form the aggregate signal. This results in the interference mechanism changing from pulse-like (in the single and two signal case) to noise-like (in the three through six UWB signal aggregate cases). The noise-like characteristic is also caused by the dithering of the UWB signal as opposed to a constant PRF that would result in a CW-like effect. In this case, the effective aggregate interference level is the sum of the individual UWB signal average power levels. The measured

[47] ITS Report at Figure 6.3.2.1.

break-lock level was -83.5 dBm/20 MHz and the reacquisition threshold was -93 dBm/20 MHz for the final test where the aggregate consisted of six individual signals. These values can be adjusted for comparison with existing RTCA and ITU-R protection limits. This would yield an adjusted measured value of -140.5 dBW/MHz that compares to the existing limit for noise-like interference of -140.5 dBW/MHz.

In summary, the aggregate measurements are in keeping with what one would expect. They show the "fill in" effect that causes a transition from pulse-like to noise-like interference. The data shows that when the aggregate interference is noise-like, the effective aggregate interference power level is the sum of the individual UWB signal average power levels. When the aggregate interference, associated with a somewhat limited number of UWB sources, is CW-like, the measured results show the interference threshold power to be that associated with the power of a single spectral line. Although these results are for a somewhat limited number of UWB signals, they are directly applicable to most of the scenarios considered in this study. These aggregate measurements also show results that are consistent with existing GPS interference protection limits. The comparison of the adjusted aggregate interference reacquisition thresholds with the existing limits of RTCA and ITU-R are summarized in Table 2-11.

Table 2-11. Comparison of Adjusted Aggregate Interference Thresholds with Existing Limits

Aggregate Interference Measurement Case	Category of Aggregate Interfering Signal Effect	Adjusted Reacquisition Threshold	Existing Limits
I	Noise-Like	-142 dBW/MHz	-140.5 dBW/MHz
II	Noise-Like	-140.5 dBW/MHz	-140.5 dBW/MHz
III	CW-Like	-154.1 dBW	-150.5 dBW
IV	CW-Like	-148 dBW	-150.5 dBW
V (6 UWB Generators)	Noise-Like	-140.5 dBW/MHz	-140.5 dBW/MHz

SECTION 3.0
ANALYSIS OVERVIEW

3.1 ANALYSIS DESCRIPTION

The measurements performed by the ITS define the interference threshold of a UWB device as a function of the UWB signal parameters (e.g., power, PRF, gating, modulation). The interference threshold is measured at the input of the GPS receiver and is used in the analysis for each specific GPS/UWB operational scenario to calculate the maximum allowable emission level at the output of the UWB device antenna. The following paragraphs describe the analysis method used.

The maximum allowable emission level from the UWB device is based on an EIRP limit. The EIRP is the power supplied to the antenna of the UWB device multiplied by the relative antenna gain of the UWB device in the direction of the GPS receiver. The maximum allowable EIRP is computed using the following equation:

$$EIRP_{max} = I_T - G_r + L_p - L_{mult} - L_{allot} - L_{man} + L_{AF} + L_{BA} - L_{safety} \quad (1)$$

where:

$EIRP_{max}$ is the maximum allowable EIRP of the UWB device (dBW or dBW/MHz);
I_T is the interference threshold of the UWB signal at the input of the GPS receiver (dBW or dBW/MHz);
G_r is the gain of the GPS antenna in the direction of the UWB device (dBi);
L_p is the radiowave propagation loss (dB);
L_{mult} is the factor to account for multiple UWB devices (dB);
L_{allot} is the factor for interference allotment (dB);
L_{man} is the factor to account for manufacturer variations in GPS receivers (dB);
L_{AF} is the activity factor of the UWB device (dB);
L_{BA} is the building attenuation loss (dB);
L_{safety} is the aviation safety margin (dB).

The following paragraphs explain each of the technical factors used in the analysis.

3.1.1 UWB Interference Threshold (I_T)

The UWB interference threshold referenced to the input of the GPS receiver is obtained from the single source interference susceptibility measurements performed by ITS as discussed in Section 2.1.1 (Tables 2-1 and 2-2). Adjustments are made to the measured interference susceptibility levels to compute the UWB interference threshold. As discussed in Section 3.3 (Tables 3-13 and 3-14), the adjustments made to the measured interference susceptibility levels are based on the individual UWB signal structure.

3.1.2 GPS Receiver Antenna Gain (G_r)

The GPS antenna gain model used in this analysis is provided in Table 3-1. The antenna gain used is based on the position of the UWB device with respect to the GPS antenna and is determined from the GPS/UWB operational scenario under consideration.

TABLE 3-1. GPS Antenna Gain Based on UWB Device Position With Respect to GPS Antenna

Off-axis Angle (Measured with Respect to the Horizon)	GPS Antenna Gain (dBi)
-90 degrees to -10 degrees	-4.5
-10 degrees to 10 degrees	0
10 degrees to 90 degrees	3

The off-axis angle measured with respect to the horizon is computed by:

$$\theta = \tan^{-1} [(h_{UWB} - h_{GPS})/D] \qquad (2)$$

where:

θ is the angle measured with respect to the horizon (degrees);
h_{UWB} is the UWB device antenna height (m);
h_{GPS} is the GPS receiver antenna height (m);
D is the horizontal separation between the GPS receiver and UWB device (m).

3.1.3 Radiowave Propagation Model (L_p)

The radiowave propagation loss is computed using the minimum distance separation between the GPS receiver and the UWB device as defined by the GPS/UWB operational scenario. The radiowave propagation model used also depends on the GPS/UWB operational scenario. By definition, "free-space" assumes that there is a line-of-sight (LOS) path between the UWB device and the GPS receiver. The radiowave propagation model described by the free-space loss equation is :

$$L_p = 20 \text{ Log } F + 20 \text{ Log } D_{min} - 27.55 \qquad (3)$$

where:

L_p is the free-space propagation loss (dB);
F is the frequency (MHz);
D_{min} is the minimum distance separation between the GPS receiver and UWB device (m).

As a result of antenna heights and terrain conditions, free-space conditions may not exist. There is a phenomenon referred to as the propagation loss breakpoint, which consists of a change in the slope of the propagation loss with distance at a radial distance from the transmitter. It is caused by the reflection of the transmitted signal by the ground. This multipath signal interferes with the direct path signal and usually occurs only in areas with clear LOS and ground reflection paths.

For the frequency range of interest, the propagation loss changes by 20 dB/decade (i.e., free-space loss) close to the transmitter, and by 40 dB/decade after the propagation loss breakpoint occurs. The propagation loss breakpoint radius from the transmitter, R_b, is calculated using the formula [48]:

$$R_b = 2.3 \times 10^{-6} \, F \, (h_t h_r) \qquad (4)$$

where:

R_b is the propagation loss breakpoint radius (mi);
F is the frequency (MHz);
h_t is the UWB device antenna height (ft);
h_r is the GPS receiver antenna height (ft).

When the minimum distance separation between the UWB device and the GPS receiver is less than R_b, the free-space propagation model should be used. When the minimum distance separation between the UWB device and the GPS receiver is greater than R_b, a propagation model that takes into account non-LOS conditions should be used.

3.1.4 Multiple UWB Devices (L_{mult})

The GPS/UWB operational scenario determines whether single or multiple UWB devices should be considered. The factor for multiple UWB devices was obtained from the multiple source (aggregate) measurements performed by ITS. Section 2.1.2 of this report, discusses the multiple UWB devices measurement results. Based on the multiple source measurements, the factor to be included in the analysis for multiple UWB devices will depend on whether the interference effect has been characterized as being pulse-like, CW-like, or noise-like. The exception is the en-route navigation operational scenario, where it is assumed that there are a large enough number of UWB devices, such that independent of the individual UWB signal parameters, the aggregate effect causes noise-like interference.

As discussed in Section 2.2.3, signals that were characterized as being pulse-like for single UWB device interactions were characterized as being noise-like when multiple UWB devices are considered. The occurrence of the transition from pulse-like to noise-like interference was verified in Measurement Case V. The number of UWB devices required for this transition to

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[48] E. N. Singer, *Land Mobile Radio Systems* (Second Edition) at 194.

occur depends on the PRF. For the 1 MHz PRF signals, the measurements show that three signals are required for the transition to occur. In the case of the 100 kHz PRF signals, the number of UWB devices necessary for the transition to occur will be much larger than the number of UWB devices under consideration in the operational scenarios. Based on the measurement results, a factor for multiple UWB devices is not included in this analysis for signal permutations that have been characterized as causing pulse-like interference with a PRF of 100 kHz.

The interference effect for UWB signals that have been characterized as being CW-like is attributed to the single interfering CW line that is coincident with a dominant C/A-code line. This was discussed in Section 2.2.3, and confirmed in Measurement Cases III and IV. Multiple UWB signals that are characterized as causing CW-like interference, do not add to determine the effective interfering signal power. A large number of UWB devices producing spectral lines would be necessary before there is a transition to a noise-like interference effect. This transition from CW-like to noise-like will not occur with the number of UWB devices under consideration in the operational scenarios. Based on the measurement results, a factor for multiple UWB devices is not included in this analysis for UWB signal permutations that have been characterized as causing CW-like interference.

UWB signals permutations with PRFs of 1 MHz, 5 MHz, and 20 MHz that have been characterized as being pulse-like, will transition to noise-like interference as the number of UWB devices is increased. This is discussed in Section 2.2.3 and verified in Measurement Case V. For these UWB signals permutations, a factor of 10 Log (number of UWB devices) is included in the analysis.

As discussed in Section 2.2.3, and verified in Measurement Case I and II, if the individual signals cause an interference effect that is noise-like, the interference effect of the multiple noise-like signals is noise-like. Based on the measurement results, for UWB signal permutations that have been characterized as causing noise-like interference, a factor of 10 Log (number of UWB devices) is included in the analysis.

3.1.5 Interference Allotment (L_{allot})

Several potential sources of interference to GPS receivers have been identified. These include but are not limited to: 1) adjacent band interference from mobile satellite service (MSS) handsets; 2) harmonics from television transmitters; 3) adjacent band interference from super geostationary earth-orbiting (super GEO) satellite transmitters[49]; 4) spurious emissions from 700 MHz public safety base, mobile, and portable transmitters; and 5) spurious emissions including harmonics from 700 MHz commercial base, mobile, and portable transmitters. Multiple sources of interference, which might individually be tolerated by a GPS receiver, may combine to create

[49] Super GEOs are geostationary earth orbiting satellites that are designed to employ a high transmit power to communicate with mobile handsets.

an aggregate interference level (e.g., noise and emissions) that could prevent the reliable reception of the GPS signal. In the GPS/UWB operational scenario, a percentage of the total allotment for all interfering sources will be attributed specifically to UWB devices.

In this analysis the percentage of the total interference allotment that is attributed to UWB devices is dependent on the minimum distance separation between the GPS receiver and the UWB device. The minimum distance separation is established by each operational scenario. For operational scenarios where the minimum distance separation is small (e.g., on the order of several meters), the UWB device is expected to be the dominant source of interference, and 100% of the total interference is allotted to UWB devices. For operational scenarios where a larger distance separation exists, there is a greater likelihood that other interfering sources will contribute to the total interference level at the GPS receiver. In these operational scenarios, 50% of the total interference is allotted to UWB devices. That is, one half of the total allowable interference is allotted to UWB and the other half is allotted to all other interfering sources combined. For the aviation operational scenarios, larger geographic areas are visible to a GPS receiver onboard an aircraft. This larger field of view will increase the number of interfering sources that can contribute to the total interference level at the receiver. In the aviation operational scenarios, 10% of the total interference is allotted to UWB devices. The factor for UWB device interference allotment is computed from 10 Log (UWB interference allotment ratio). For example, if the UWB device interference allotment is 50% (a ratio of 0.5), a 3 dB factor is included in the analysis.

3.1.6 GPS Receiver Variation (L_{man})

The ITS measurement effort did not consider multiple samples of each model of GPS receiver. Therefore, it is not possible to determine if there is a statistical variation in the performance of GPS receivers. As an estimate, a 3 dB factor has been included to take into account likely variations among GPS receivers of the same model as well as variations in GPS receivers from different manufacturers.

3.1.7 UWB Device Activity Factor (L_{AF})

The activity factor represents the percentage of time that the UWB device is actually transmitting. For example, a UWB device that is transmitting continuously will have an activity factor of 100%, no matter what PRF, modulation, or gating percentage is employed. The activity factor is only applicable when multiple UWB devices are considered in the GPS/UWB operational scenario. Some UWB devices are expected to have inherently low activity factors such as those that are manually activated with a trigger or "deadman" switch. Others will likely have high activity factors such as a UWB local area network. Since It was not possible to estimate practical values of activity factors for each potential UWB application, an activity factor of 100% (a ratio of 1) was used in all of the operational scenarios considered in this analysis. Thus, the activity factor used is set equal to 0 dB (i.e., 10 Log (1)).

3.1.8 Building Attenuation (L_{BA})

For GPS/UWB operational scenarios that consider the use of UWB devices operating indoors a building attenuation factor is included. ITS has conducted building attenuation loss measurements at 912, 1920, and 5990 MHz.[50] The measurements were performed for different buildings representing typical residential and high rise office construction. Based on the results of these measurements, whenever the UWB device is considered to be operating indoors an average building attenuation of 9 dB is used.

3.1.9 Aviation Safety Margin (L_{safety})

When the GPS/UWB operational scenario involves aviation applications using GPS (e.g., en-route navigation and non-precision approach landing) a safety margin is appropriate. The aviation safety margin takes into account sources of radio-frequency interference that are real but not quantifiable (e.g., multipath). A safety margin of 6 dB is included for GPS receivers used in aviation applications.[51]

3.1.10 GPS Receiver Architecture

Interference susceptibility measurements were performed on the C/A-code and semi-codeless GPS receiver architectures. The GPS receiver architecture examined in the analysis are different depending upon the operational scenario under consideration. In those where the GPS receivers are used in moving vehicles (terrestrial, maritime, and railway), the C/A-code architecture was used. In the surveying operational scenario, where the GPS receiver is not moving (or moving very slowly), the semi-codeless receiver architecture was used. For the en-route navigation and non-precision approach landing operational scenarios a TSO-C129a compliant GPS receiver is used.[52]

3.2 DEVELOPMENT OF THE GPS/UWB OPERATIONAL SCENARIOS

As discussed in the previous section, the measurements of the maximum tolerable interference threshold at the input to the GPS receiver is used in this analysis to compute the maximum allowable EIRP of the UWB device. The operational scenario is necessary to relate

[50] National Telecommunications and Information Administration, Institute for Telecommunication Sciences, NTIA Report 95-325, Building Penetration Measurements From Low-height Base Stations at 912, 1920, and 5990 MHz, at 43.

[51] ITU-R M.1477 at Annex 5.

[52] The measurement results of the C/A-code TSO-C129a receiver are not available at this time. The analysis results that are presented are based on the measurements for the non-aviation C/A-code receiver. Although not aviation certified, it is representative of the architecture used by aviation in these applications. When data on the TSO-C-129a receiver is available, the results of the analysis may be revised.

the interference level at the input of the GPS receiver to the output of the UWB device. The GPS/UWB operational scenarios establish: the minimum distance separation between the GPS receiver and the UWB device; the appropriate antenna coupling; the applicable radio wave propagation model; whether single or multiple UWB devices should be considered; and any other scenario specific factors (e.g., building attenuation and aviation safety margin).

On August 31, 2000, NTIA published a Notice in the Federal Register announcing a series of public meetings to be held to gather information to be used by NTIA in developing the operational scenarios for assessing the potential interference to GPS receivers from UWB devices.[53] Meetings were held on September 7 and 27, and December 7 giving the Federal agencies and the public opportunities to present documents related to the development of GPS/UWB operational scenarios. Documents were submitted by: Multispectral Solutions Inc., the National Oceanic and Atmospheric Administration/National Ocean Science/National Geodetic Survey, NTIA, Time Domain Corporation, the USCG, and the U.S. GPS Industry Council. The specific proposals for operational scenarios included GPS receivers used in the following applications[54]:

- Public Safety (E-911 embedded in a cellular phone);
- Public Safety (emergency response vehicles);
- Geographic Information Systems;
- Precision Machine Control;
- Maritime (constricted waterway navigation, harbor navigation, docking and lock operations;)
- Railway (positive train control);
- Surveying;
- Aviation (en-route navigation and non-precision approach landings).

In addition to these specific GPS/UWB operational scenarios, NTIA proposed a general operational scenario for GPS receivers used for terrestrial applications that considered multiple UWB device interactions.

As a result of the three public meetings, five categories of GPS applications are considered in the development of the GPS/UWB operational scenarios: terrestrial, maritime, railway, surveying, and aviation. The operational scenario proposals also considered several UWB device applications. The UWB device applications include: embedded functions in a mobile phone, wireless local area networks, and short-range communication systems.

[53] NTIA Notice at 1.

[54] All of the documents from the public meetings are available upon request from the NTIA Office of Spectrum Management or from the NTIA website.

3.2.1 Terrestrial Applications

The specific operational scenario proposals for the terrestrial use of GPS receivers include: public safety, geographic information systems, and precision machine control.[55] The operational scenario proposals for terrestrial GPS receivers are all based on a minimum distance separation between the GPS receiver and UWB device of 2 meters. Although this minimum distance separation may in some cases be applicable for assessing interference from a single UWB device, it is not used when assessing interference to GPS receivers from multiple UWB devices (10 meter minimum distance separation). The single UWB device and multiple UWB device operational scenarios for terrestrial applications are considered in this analysis.

3.2.1.1 Single UWB Device

In the terrestrial operational scenario where a single UWB device interaction is considered, a minimum distance separation between the GPS receiver and the UWB device of 2 meters is used. At a minimum distance separation of 2 meters, it is appropriate to only consider the outdoor operation of UWB devices.

In the single UWB device terrestrial operational scenario, an antenna height of 3 meters is used for the GPS receiver and the UWB device. Based on the antenna model provided in Table 3-1, the antenna gain for the GPS receiver used in this operational scenario is 0 dBi.

For the GPS receiver and UWB device antenna heights of 3 meters, the expected propagation loss breakpoint radius is 568 meters. Since the minimum distance separation is much less than the expected propagation loss breakpoint radius, the free-space propagation model is applicable.

A summary of the technical factors associated with the single UWB device terrestrial operational scenario is provided in Table 3-2.

3.2.1.2 Multiple UWB Devices

After reviewing the operational scenario proposals it is clear that the use of GPS for terrestrial applications is extremely diverse. This makes it difficult to identify a single representative operational scenario to be used in assessing the potential interference to terrestrial GPS receivers from multiple UWB devices. At the December 7, 2000 GPS/UWB operational scenario meeting NTIA presented an operational scenario proposal that considered interference to a terrestrial GPS receiver from multiple UWB devices.[56] In the analysis of multiple UWB devices both indoor and outdoor operation of UWB devices is considered.

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[55] U.S. GPS Industry Council Submission to NTIA GPS/UWB Operational Scenario Meeting (Sept. 7, 2000).

[56] National Telecommunications and Information Administration, *Proposal for a General Operational Scenario for Assessing Potential Interference to Terrestrial Global Positioning System Receivers from Ultrawideband Transmission Systems* (Dec. 7, 2000).

TABLE 3-2. Technical Factors for the Single UWB Device Terrestrial Operational Scenario

Technical Factors	Value
GPS Receiver Antenna Gain	0 dBi
GPS Antenna Height	3 meters
UWB Device Antenna Height	3 meters
Minimum Distance Separation	2 meters
Propagation Model	Free-space
Interference Allotment to UWB Devices	0 dB (100%)
Variations in GPS Receivers	3 dB
Multiple UWB Devices	1 UWB device
Activity Factor for Each UWB Device	0 dB (100%)
Building Attenuation	0 dB
GPS Receiver Architecture	C/A-code

In the multiple UWB device terrestrial operational scenario, a minimum distance separation of 10 meters was established between the GPS receiver and a UWB device that is used outdoors. This was the distance separation that was presented at the GPS/UWB operational scenario meeting and is a reasonable to use when multiple UWB devices are being considered. For indoor operation, the UWB device is positioned above the GPS receiver (e.g., second floor of a building). The minimum distance separation is computed from the slant range with the GPS receiver located 5 meters from the building and the UWB device 10 meters above the GPS receiver. The following equation is used to compute the minimum distance separation:

$$D_{min} = ((h_{GPS} - h_{UWB})^2 + D^2)^{0.5} \quad (5)$$

where:

h_{GPS} is the height of the GPS receiver antenna (m);
h_{UWB} is the height of the UWB device antenna (m);
D is the horizontal separation between the GPS receiver and UWB device antennas (m).

Based on the model given in Table 3-1 the antenna gain for the GPS receiver is 0 dBi and 3 dBi for outdoor and indoor operation of UWB devices respectively.

For a distance separation of 10 meters it is reasonable to consider multiple UWB devices. Four UWB devices each located 10 meters from the GPS receiver are considered in the multiple UWB terrestrial operational scenario.

Based on the established operational scenario an antenna height of 3 meters for the GPS receiver is used. An antenna height of 3 meters (outdoor operation) and 10 meters (indoor operation) is used for the UWB devices. Using these antenna heights the expected propagation loss breakpoint radii are 568 meters for UWB devices with a 3 meter antenna height and 1.9 kilometers for UWB devices with a 10 meter antenna height. Since the distance separation used in the multiple UWB general terrestrial operational scenario is less than the expected propagation loss breakpoint radii, the free-space propagation model is applicable.

A summary of the technical factors associated with the multiple UWB device terrestrial operational scenario is provided in Table 3-3.

TABLE 3-3. Technical Factors for the Multiple UWB Device Terrestrial Operational Scenario

Technical Factors	Value (Outdoor Operation)	Value (Indoor Operation)
GPS Receiver Antenna Gain	0 dBi	3 dBi
GPS Antenna Height	3 meters	3 meters
UWB Device Antenna Height	3 meters	10 meters
Minimum Distance Separation	10 meters	8.6 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	(3 dB) 50%	3 (dB) 50%
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	4 UWB devices	4 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	C/A-code	

3.2.2 Maritime Applications

The operational scenario proposals for the maritime use of GPS receivers include: navigation in constricted waterways, harbor navigation, docking operations, navigation around bridges, and lock operations.[57] The USCG has indicated that the limiting operational scenario for maritime applications is when the GPS receiver is used for navigation in constricted waterways. In this analysis, indoor and outdoor UWB device operation is considered.

In the two operational scenario proposals for navigation in constricted waterways, the GPS receiver antenna is assumed to be mounted on the mast of the vessel. Therefore, the minimum distance separation has both a horizontal and vertical component. The minimum distance separation between the GPS receiver and the UWB device is computed from the slant range using Equation 5.

The first restricted waterway operational scenario implementation uses an antenna height of 45 feet (13.5 meters) and a horizontal separation from the UWB devices of 125 feet (37.5 meters). The second implementation uses an antenna height of 25 feet (7.5 meters) and a horizontal separation from the UWB devices of 170 feet (51 meters). An antenna height of 3 meters (outdoor operation) and 10 meters (indoor operation) is used for the UWB devices. The computed minimum distance separations for the two implementations in the maritime navigation, constricted waterways operational scenario is given in Table 3-4.

TABLE 3-4. Minimum Distance Separations for the Maritime Navigation in Constricted Waterways Operational Scenario

GPS Receiver Antenna Height (Meters)	UWB Device Antenna Height (Meters)	Minimum Distance Separation (Meters)
13.5	3	38.9
7.5	3	51.2
13.5	10	37.7
7.5	10	51.1

For these minimum distance separations it is reasonable to consider multiple UWB devices. Four UWB devices each located at the minimum distance separations are considered in the maritime navigation in constricted waterways operational scenario.

Based on the model given in Table 3-1, when the off-axis angle is greater than -10 degrees the GPS antenna gain in the direction of the UWB device is 0 dBi. When the off-axis angle is less than -10 degrees the USCG has specified that the GPS antenna gain in the direction of the UWB device is -3 dBi.

[57] United States Coast Guard Navigation Center Submission to NTIA GPS/UWB Operational Scenario Meeting (Sept. 27, 2000).

Based on the GPS receiver antenna heights and the UWB device antenna heights the expected propagation loss breakpoint radii are computed and given in Table 3-5. Since the computed minimum distance separations are much less than the expected propagation loss breakpoint radii the free-space propagation model is applicable.

TABLE 3-5. Expected Propagation Loss Breakpoint Radii for the Maritime Navigation in Constricted Waterways Operational Scenario

GPS Receiver Antenna Height (Meters)	UWB Device Antenna Height (Meters)	Propagation Loss Breakpoint Radii (Kilometers)
13.5	3	2.5
7.5	3	1.4
13.5	10	8.5
7.5	10	4.7

A summary of the technical factors associated with the maritime navigation in constricted waterways operational scenario is provided in Table 3-6.

3.2.3 Railway Applications

The operational scenario proposal for the railway use of GPS receivers is for positive train control (PTC).[58] The specifics of this operational scenario proposal were provided by the NTIA.[59] In this analysis, indoor and outdoor operation of UWB devices is considered.

In the operational scenario proposal for PTC the GPS receiver antenna is mounted on top of the train. Therefore, the minimum distance separation has both a horizontal and vertical component. The minimum distance separation between the GPS receiver and the UWB device is computed from the slant range using Equation 5.

The GPS receiver antenna in the railway PTC operational scenario has an antenna height of 10 meters and a horizontal separation from the UWB devices of 7 meters. An antenna height of 3 meters (outdoor operation) and 10 meters (indoor operation) is used for the UWB devices. The computed minimum distance separations are 9.8 meters for outdoor UWB device operation and 7 meters for indoor UWB device operation.

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[58] 1999 FRP at 2-25.

[59] *Summary of GPS/UWB Operational Scenarios* Prepared by the NTIA (Nov. 20, 2000) (hereinafter "NTIA Summary").

TABLE 3-6. Technical Factors for the Navigation in Constricted Waterways Operational Scenario

Technical Factors	Value (Outdoor Operation)	Value (Indoor Operation)
GPS Receiver Antenna Gain	-3 and 0 dBi	0 dBi
GPS Antenna Height	13.5 and 7.5 meters	13.5 and 7.5 meters
UWB Device Antenna Height	3 meters	10 meters
Minimum Distance Separation	38.9 and 51.2 meters	37.7 and 51.1 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	3 dB (50%)	3 dB (50%)
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	4 UWB devices	4 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	C/A-code	

Using the model given in Table 3-1, the antenna gain for the GPS receiver antenna is 0 dBi for indoor UWB device operation and -4.5 dBi for outdoor UWB device operation.

For these minimum distance separations, it is reasonable to consider multiple UWB devices. Three UWB devices each located at the minimum distance separation will be considered in the railway PTC operational scenario.

Based on the GPS receiver antenna heights and the UWB device antenna heights the expected propagation loss breakpoint radii are 1.9 kilometers for outdoor UWB device operation and 6.3 kilometers for indoor UWB device operation. Since the computed minimum distance separations are much less than the expected propagation loss breakpoint radii the free-space propagation model is applicable.

A summary of the technical factors associated with the railway PTC operational scenario is provided in Table 3-7.

TABLE 3-7. Technical Factors for the Railway PTC Operational Scenario

Technical Factors	Value (Outdoor Operation)	Value (Indoor Operation)
GPS Receiver Antenna Gain	-4.5 dBi	0 dBi
GPS Antenna Height	10 meters	10 meters
UWB Device Antenna Height	3 meters	10 meters
Minimum Distance Separation	9.8 meters	7 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	3 dB (50%)	3 dB (50%)
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	3 UWB devices	3 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	C/A-code	

3.2.4 Surveying Applications

Two operational scenario proposals were provided for the surveying use of GPS receivers.[60] The surveying operational scenarios considered interference from both single and multiple UWB device interactions.

In the surveying operational scenarios the GPS receiver is located below the antenna of the UWB device. When a single UWB device is considered a minimum distance separation of 30 meters was proposed. For multiple UWB devices it was proposed that the first UWB device be located 30 meters from the GPS receiver. Two additional UWB devices are located at distances between 300 to 750 meters from the GPS receiver.

If an antenna height of 3 meters is used for the GPS receiver and 10 meters is used for the UWB device, the expected pathloss breakpoint radius is 1.2 kilometers. For the surveying operational scenarios the minimum distance separation is less than the expected pathloss breakpoint radius, therefore the free-space propagation model is applicable.

A summary of the technical factors associated with the surveying operational scenarios is provided in Table 3-8.

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[60] National Oceanic and Atmospheric Administration/National Ocean Service/National Geodetic Survey Submission to NTIA GPS/UWB Operational Scenario Meeting (Sept. 27, 2000).

TABLE 3-8. Technical Factors for the Surveying Operational Scenarios

Technical Factors	Value (Single UWB Device)	Value (Multiple UWB Devices)
GPS Receiver Antenna Gain	3 dBi	3 dBi, 0 dBi
GPS Antenna Height	3 meters	3 meters
UWB Device Antenna Height	10 meters	10 meters
Minimum Distance Separation	30 meters	30, 300, 750 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	3 dB (50%)	3 dB (50%)
Variations in GPS Receivers	3 dB	3 dB
Multiple UWB Devices	1 UWB device	3 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	0 dB
GPS Receiver Architecture	Semi-Codeless	

3.2.5 Aviation Applications [61]

The operational scenario proposals for the aviation use of GPS receivers include: en-route navigation and non-precision approach landings.[62] En-route navigation is a phase of navigation covering operations between a point of departure and termination of the flight. Non-precision approach landing is a standard instrument approach procedure using a ground-based system in which no electronic glide slope is provided.[63]

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[61] Another aviation application that was discussed at the NTIA operational scenario meetings, was the use of GPS receivers in airport surface movement operations. Sufficient information is not available at this time to include an assessment of this operational scenario in this report. This operational scenario is being actively addressed within RTCA and the results will be made available when the study is complete.

[62] NTIA Summary at 10.

[63] Glide slope is a descent profile determined for vertical guidance during a final approach.

3.2.5.1 En-Route Navigation

For the en-route navigation operational scenario, the aircraft with the GPS receiver is at an altitude of 1,000 feet.[64] The maximum LOS distance (d_{LOS}) for an aircraft at an altitude of 303 meters (1,000 feet) is given by:

$$d_{LOS} = 3.57\ (k)^{0.5}\ ((h_{UWB})^{0.5} + (h_{GPS})^{0.5}) \qquad (6)$$

where:

k is the effective Earth radius factor;
h_{UWB} is the antenna height of the UWB device (m);
h_{GPS} is the height of the GPS receiver antenna located on the aircraft (m).

Using an antenna height of 3 meters for the UWB device and a typical value of k in a temperate climate of 1.33, the computed LOS distance for the aircraft is 78.5 kilometers. Since such a large geographic area is visible to an aircraft at this altitude, the impact of multiple UWB devices is considered for the aviation en-route navigation operational scenario.

To compute the aggregate emission level into the GPS receiver from multiple UWB devices a computer model developed by NTIA is used. This computer model computes the power-sum aggregate emission level from a surface density of UWB devices with the same emission frequency and emission level. The computer model assumes that all of the UWB devices are radiating in the direction of the airborne GPS receiver. The UWB devices are distributed uniformly in concentric rings on a spherical dome of the Earth's surface as shown in Figure 3-1 such that the distance from any UWB device to its closest neighbor remains approximately constant throughout the distribution. A 4/3 Earth-radius model is assumed for ray bending effects, and the free-space propagation model is employed for propagation loss computations. A detailed description of the computer model is provided in a separate NTIA report.[65]

Determining the density of a large number of UWB devices is a key factor affecting the aggregate interference to a GPS receiver used for en-route navigation. Factors that should be considered when estimating the density of a large number of UWB devices include: population; assumed rate for technology penetration; and activity factor. In the absence of such information, this analysis computes the maximum allowable EIRP as a function of active UWB device density.

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[64] Document No. RTCA/DO-235, *Assessment of Radio Frequency Interference Relevant to the GNSS* (Jan. 27, 1997) at A-2 (hereinafter "DO-235").

[65] National Telecommunications and Information Administration, U.S. Department of Commerce, NTIA Special Publication 01-43, Assessment of Compatibility Between Ultra-Wideband Devices and Selected Federal Systems (Jan. 2001) at 5-5.

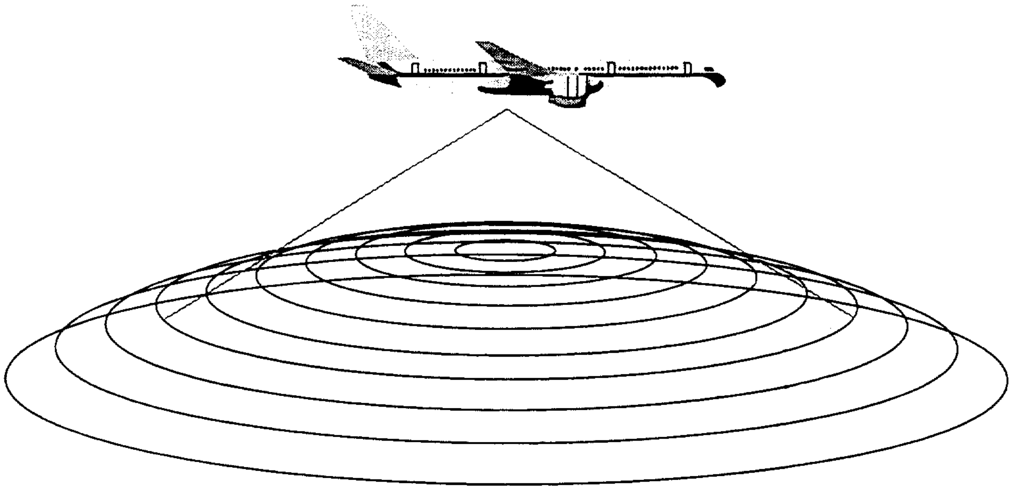

Figure 3-1. Airborne Geometry for the NTIA Aggregate Emitter Model

Indoor and outdoor operation of UWB devices is considered in the aviation en-route navigation operational scenario. Since it is not possible to estimate what percentage of the UWB devices are operating indoor versus those operating outdoor, two cases are considered. In the first case all of the UWB devices are operating outdoors and in the second case all of the UWB devices are operating indoors.

In the en-route operational scenarios, the GPS receiver antenna is located on top of the aircraft. In a previous analysis of terrestrial interference to GPS receivers, an antenna gain below the aircraft of -10 dBi was used.[66] Since there are no specifications on antenna gain below the aircraft and sufficient installed antenna pattern data is lacking on civil aircraft the value of antenna gain of -10 dBi will be used in the aviation en-route navigation operational scenario.

Since en-route navigation is a safety-of-life function it is appropriate to include a 6 dB safety margin in this operational scenario.

A summary of the technical factors associated with the aviation en-route navigation operational scenario is provided in Table 3-9.

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[66] DO-235 at F-13.

TABLE 3-9. Technical Factors for the Aviation En-Route Navigation Operational Scenario

Technical Factors	Value (Outdoor Operation)	Value (Indoor Operation)
GPS Receiver Antenna Gain	-10 dBi	-10 dBi
GPS Antenna Height	303 meters	303 meters
UWB Device Antenna Height	3 meters	3 meters
Minimum Distance Separation	303 meters	303 meters
Propagation Model	Free-space	Free-space
Interference Allotment to UWB Devices	10 dB (10%)	10 dB (10%)
Variations in GPS Receivers	3 dB	3 dB
Aviation Safety Margin	6 dB	6 dB
Multiple UWB Devices	Variable	Variable
Activity Factor for Each UWB Device	0 dB (100%)	0 dB (100%)
Building Attenuation	0 dB	9 dB
GPS Receiver Architecture	C/A-code	

3.2.5.2 Non-Precision Approach Landing

The FAA distinguishes a precision approach from a non-precision approach landing by requiring a precision approach to have a combined lateral and vertical (glide slope) guidance. The term non-precision approach refers to facilities without a glide slope. The FAA maintains the same level of flight safety for non-precision approaches as it does for precision approaches. They achieve this equity by requiring a much larger displacement area at the missed approach point and a higher minimum descent height (MDH) for the non-precision approach landings than they do for the precision approach landings. The MDH is the lowest altitude to which descent shall be authorized for procedures not using a glide slope (vertical guidance).

Associated with each non-precision approach landing segment there is a MDH. The MDH is computed by:

$$\text{MDH} = 250 \text{ feet} + (\text{Obstacle Height}) \tag{7}$$

If there are no obstructions, then the MDH is 250 feet. Assuming that a UWB device can be located on top of an obstacle, or at ground level within an obstacle-free zone, and assuming that the GPS antenna is located 7 feet above the aircraft control point, the following equation is used to compute the minimum distance separation between the GPS receiver used for non-precision approach landings and a UWB device:

$$D_{min} = 257 - TSE \tag{8}$$

where TSE is the Total System Error.

The TSE comprises both the aircraft and its navigation system tracking errors. It is the difference between true position and desired position. The TSE is computed from the root-sum-square of the Flight Technical Error (FTE) and the Navigation System Error (NSE):

$$TSE = ((FTE)^2 + (NSE)^2)^{0.5} \tag{9}$$

The FTE is the error contribution of the pilot using the presented information to control aircraft position. The NSE is the error attributable to the navigation system in use. It includes the navigation sensor error, receiver error, and path definition error.

The 95% probability (2σ) value for the FTE is 100 feet.[67] The NSE for the vertical guidance for the 3σ value is 103 feet corresponding to the minimum accuracy requirements for vertical guidance equipment.[68] Based on the 3σ value, the 2σ value for NSE is then 68.6 feet. Using Equation 9 the TSE is then 121.2 feet. Using Equation 8, the minimum distance separation between the GPS receiver used for the non-precision approach landings and a UWB devices is 135.8 feet.

In the previous analyses that have been performed examining interference from terrestrial emitters to a GPS receiver used for precision approach landings it was assumed that a single emitter was below the aircraft and located at the Category I decision point. The effect of multiple interfering emitters was not considered in this analysis. A methodology was presented in RTCA Working Group 6 to address multiple interfering sources.[69] As an aircraft passes over the UWB devices, the antenna located on top of the aircraft projects a plane on the surface of the Earth as shown in Figure 3-2. As shown in Figure 3-2, point P represents the GPS receiver antenna. The surface E represents the plane containing the interfering sources. The parameter h is the minimum distance from point P to plane E. The parameter d is the distance from points on plane E whose propagation loss differs from the minimum loss at distance h by a fixed propagation loss ratio (LR). The parameter r is the radius of the plane (circle) containing the points of the fixed propagation loss ratio. The radius of this circle is given by:

$$r = h\,(LR-1)^{0.5} \tag{10}$$

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[67] Document No. RTCA/DO-208, *Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using GPS* (July 1991) at E-4.

[68] *Id.* at 34.

[69] R. J. Erlandson, Rockwell Collins, *UWB Cumulative RFI Effects Aspects for Aviation Precision Approach Scenarios,* SC-159 WG 6 Presentation (Oct. 25, 2000).

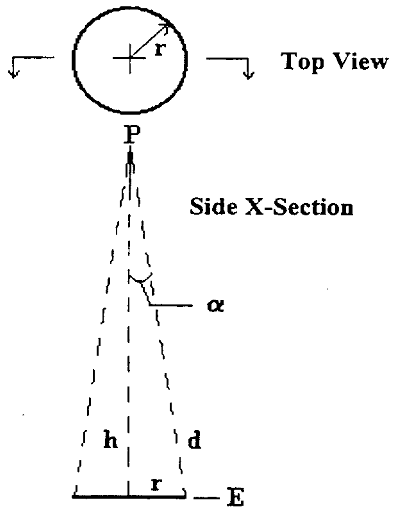

Figure 3-2. Airborne Antenna Projection Geometry

A derivation of Equation 10 is provided in Appendix A. Another factor to be considered is the variation in antenna gain. This can be examined from the angle α in Figure 3-2 using the following equation:

$$\alpha = \cos^{-1} (1/(LR)^{0.5}) \qquad (11)$$

A derivation for Equation 11 is also provided in Appendix A.

In determining a representative value for LR, the variation in antenna gain should be taken into consideration. Although the antenna gain specified in Table 3-1 shows a constant antenna gain in the region of -90 to -10 degrees, the actual antenna pattern contains many peaks and nulls (maximum and minimum values of antenna gain).[70] Therefore, the value of LR should be selected to minimize the variation in antenna gain, thereby permitting the use of a single representative antenna gain in the analysis. Using Equation 10 with the minimum distance separation of 136 feet and a propagation loss ratio of 0.1 dB, a circle with a radius of 20.7 feet (41.4 feet in diameter) is computed. For the fixed propagation loss ratio of 0.1 dB, the computed antenna cone angle (α) is 8.68 degrees. This angle is assumed to be small enough to neglect antenna gain variations and will permit the use of a single value of antenna gain in the analysis.

A circle with a diameter of 41.4 feet is large enough to contain several UWB devices. In the aviation non-precision approach landing operational scenario four UWB devices are considered.

[70] DO-235 at Appendix E Annex 2.

In the non-precision approach landing operational scenario, the GPS receiver antenna is located on top of the aircraft. As discussed in the en-route navigation operational scenario, a previous analysis of terrestrial interference to GPS receivers used an antenna gain below the aircraft of -10 dBi. Since there are no specifications on antenna gain below the aircraft and sufficient installed antenna pattern data is lacking on civil aircraft an antenna gain of -10 dBi will be used in this operational scenario.

In this operational scenario, the minimum distance separation between the GPS receiver and the UWB devices is 136 feet. Typically, when the aircraft is at this altitude there are no buildings or structures that are located along the area approaching the runway. Therefore, this analysis only considers UWB devices that are operating outdoors.

Since non-precision approach landings are considered a safety-of-life function it is appropriate to include a 6 dB safety margin in this operational scenario.

A summary of the technical factors associated with the aviation non-precision approach landing operational scenario is provided in Table 3-10.

TABLE 3-10. Technical Factors for the Aviation Non-Precision Approach Landing Operational Scenario

Technical Factors	Value
GPS Receiver Antenna Gain	-10 dBi
GPS Antenna Height	41.4 meters
UWB Device Antenna Height	3 meters
Minimum Distance Separation	41.4 meters
Propagation Model	Free-space
Interference Allotment to UWB Devices	10 dB (10%)
Variations in GPS Receivers	3 dB
Aviation Safety Margin	6 dB
Multiple UWB Devices	4 UWB devices
Activity Factor for Each UWB Device	0 dB (100%)
Building Attenuation	0 dB
GPS Receiver Architecture	C/A-code

3.3 ANALYSIS RESULTS

The results of the analysis are presented in this section. Prior to using the measured interference susceptibility levels (I_{meas}) in the analysis, adjustments must be made based on the signal structure of the interfering signal to compute the UWB interference threshold (I_T).

For signals that have been characterized as causing CW-like interference, the value of I_T used in the analysis is based on the power in a single spectral line. As such, the computed values of maximum allowable EIRP represents the power in a single CW-line, independent of the modulation employed.

For interfering signals that have been characterized as causing pulse-like interference, the value of I_{meas} used to compute I_T, was the average measured value. In those cases where neither a break-lock (BL) or reacquisition (RQT) threshold could be measured, this was referred to as Did Not Break Lock (DNBL). The value of I_{meas} used in the analysis was the maximum available UWB power. It should be noted that the maximum available UWB power was limited by the peak power of the UWB generator. In the case of UWB signals employing 20% gating, where neither a BL or RQT condition was obtained, the maximum available UWB power was reduced by a factor of 10 Log (gating percentage) to obtain an average value for I_T. This can result in an incongruous situation, where the computed value of maximum allowable EIRP is lower for the gated UWB signal versus the non-gated signal.

The GPS receivers considered in the analysis employ one of two receiver architectures: C/A-code and semi-codeless. A GPS receiver that employs C/A-code architecture processes the transmitted C/A-code signal, which has a null-to-null bandwidth of 2.046 MHz. A GPS receiver that employs the semi-codeless architecture, processes the transmitted P-code signals at the L1 and L2 frequencies to provide a measure of ionospheric delay. This permits a correction to psuedorange for ionospheric effects. The P-code signal has a null-to-null bandwidth of 20.46 MHz. Since the signals processed by the two GPS receiver architectures have different spectral characteristics, adjustments must be made to the values of I_{meas} before they can be used in the analysis.

The C/A signal has an approximate $sinc^2$ power spectral envelope with a null-to-null bandwidth of 2.046 MHz. GPS employs a family of short pseudo-random codes known as Gold codes to generate the different pseudo-random sequences of the C/A-code signal. Due to the short period (1 ms) length Gold code there are distinct spectral lines spaced 1 kHz apart. The spectral lines deviate from the $sinc^2$ envelope enough to create dominant spectral lines that are more vulnerable to CW interference. In the measurements when a UWB signal structure contains spectral lines, one of the lines is placed close (nominally 500 Hz) to a dominant GPS spectral line. As discussed in Section 2.2, when a UWB signal structure contains spectral lines an adjustment is made to the measured interference susceptibility level to determine the power in the spectral line prior to using this level in the analysis. An adjustment is made to the measured interference susceptibility levels when gating is employed. When the UWB signal appears noise-like an adjustment must also be made to the measured interference susceptibility level to correct